

Isospin symmetry breaking nucleon-nucleon potentials and nuclear structure

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Abstract

Modern nucleon-nucleon (NN) potentials, which accurately fit the nucleon-nucleon scattering phase shifts, contain terms which break isospin symmetry. The effects of these symmetry violating terms on the bulk properties of nuclear matter are investigated. The predictions of the charge symmetry breaking (CSB) terms are compared with the Nolen-Schiffer (NS) anomaly regarding the energies of neighboring mirror nuclei. We find that, for a quantitative explanation of the NS anomaly, it is crucial to include CSB in partial waves with $L > 0$ (besides 1S_0) as derived from a microscopic model for CSB of the NN interaction.

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Isospin symmetry (or charge independence) is invariance under any rotation in isospin space. Due to the mass difference between up and down quarks and due to the electromagnetic interaction, this symmetry is slightly violated which is referred to as isospin symmetry breaking (ISB) or charge independence breaking. *Charge symmetry* is invariance under a rotation by 180° about the y -axis in isospin space if the positive z -direction is associated with the positive charge. The violation of this symmetry is known as charge symmetry breaking (CSB). Obviously, CSB is a special case of ISB.

ISB of the strong nucleon-nucleon (NN) interaction means that, in the isospin $T = 1$ state, the proton-proton ($T_z = +1$), neutron-proton ($T_z = 0$), or neutron-neutron ($T_z = -1$) interactions are (slightly) different, after electromagnetic effects have been removed. CSB of the NN interaction refers to a difference between proton-proton (pp) and neutron-neutron (nn) interactions, only. For reviews on these matters, see Refs. [1,2].

In recent years, a new generation of realistic NN potentials has been developed which take ISB of the NN interaction into account and, therefore, yield very accurate fits of the proton-proton and proton-neutron (pn) scattering phase shifts [3–5]. Since these fits are based on the same phase shift analysis by the Nijmegen group [6] and yield a value for the χ^2/datum very close to one, these various potentials could be called phase-shift equivalent NN interactions. The interactions by the Nijmegen group (Nijm1, Nijm2, Reid93) [3], the Argonne group (ArgV18) [4] and the charge-dependent Bonn potential (CDBonn) [5] describe the long-range part of the NN interaction in terms of the one-pion-exchange model, accounting for the mass-difference between π^0 and the charged pions π^+ and π^- . This distinction between the exchange of a neutral pion and charged pions is one origin of ISB in the resulting NN interactions. It yields different phase shifts for pp scattering (only neutral pion exchange) as compared to pn scattering in partial waves with isospin $T = 1$. Additional ISB terms have to be included in the 1S_0 state to achieve an accurate fit of pp and pn phase shifts in that partial wave.

The new NN interactions also account for the mass difference between proton and neutron. This gives rise to a difference in the matrix elements of the meson-exchange interaction

between two protons and two neutrons. This breaks charge-symmetry, but only by a very small amount. Additional CSB terms are included in the ArgV18 and CDBonn potentials to reproduce the difference in the empirical nn and pp scattering lengths, after subtracting the effects of electromagnetic interactions.

It is the aim of this brief report to study the effects of ISB on the calculated bulk properties of nuclear systems. Are these symmetry breaking effects similar in all these NN interactions? What is the influence of the ISB terms on the calculated symmetry energy and saturation properties of nuclear matter? And more specifically, do the CSB terms explain the so-called Nolen-Schiffer anomaly [7], the energy difference between neighboring mirror nuclei, which cannot be explained by the electromagnetic interaction?

For that purpose we have performed Brueckner-Hartree-Fock (BHF) calculations of nuclear matter, in which we distinguish between pp , pn and nn interactions. As a reference we have also performed BHF calculations, in which the pp and nn interactions have been replaced by the corresponding pn interaction. The Bethe-Goldstone equation has been solved by determining a self-consistent single-particle spectrum for the hole states, which is extended in a continuous way to states with momenta k larger than the Fermi momentum k_F . For very high momenta, for which this prescription would yield a repulsive single-particle potential, the single-particle energy has been assumed to be identical to the kinetic energy. Such a continuous choice for the single-particle spectrum yields larger binding energies than the conventional choice (single-particle energy equal to kinetic energy for $k \geq k_F$) and seems to reduce the effects of three-body correlations in the hole-line expansion [8].

The interactions CDBonn, ArgV18, Nijm1, Nijm2 and Reid93 are quite different, although they are phase-shift equivalent and agree to a large extent in the OPE contribution. This is demonstrated in Table I, which presents some results calculated for nuclear matter at the empirical value for the saturation density ($\rho_0 = 0.17 \text{ fm}^{-3}$, which corresponds to a Fermi momentum of symmetric nuclear matter of $k_F = 1.36 \text{ fm}^{-1}$). The results for the energy of nuclear matter calculated in the Hartree-Fock (HF) approximation (E_{HF} , second column of Table I) range from 6.06 MeV per nucleon obtained from the CDBonn potential

to 35.62 MeV per nucleon in the case of the Nijm2 interaction. The discrepancy between these HF results and the empirical value of -16 MeV per nucleon reflects the importance of NN correlations to be included in the nuclear structure calculation. It is worth noting that these modern models of the NN interaction are much “softer” than older versions of a realistic NN interaction: e.g. the Reid soft-core potential [9] yields a HF energy of 175 MeV per nucleon. It should also be mentioned that the NN interactions, which contain non-local terms like the Nijm1 and the CDBonn potential are softer, i.e. yield less repulsive HF energies, than the NN interactions defined in terms of local potentials [10].

If effects of NN correlations are included by employing the BHF approach, the various models of the NN interaction yield results (see first column in Table I) which are rather close to each other, the largest difference being 3 MeV, and also fairly close to the empirical energy. The NN interactions with weaker tensor force (CDBonn and ArgV18) [11] yield more binding energy than those which contain a stronger tensor force and the softer nonlocal potentials CDBonn and Nijm1 tend to predict larger binding energies than corresponding local interactions. This can easily be understood: Stiff potentials and those with a large tensor component, receive a large part of the attraction in the T-matrix from terms of second and higher order in the potential V . Due to Pauli and dispersion effects these attractive contributions are quenched in the G -matrix. If two NN interactions fit the same NN phase shifts, therefore yield the same T-matrix, the G -matrix elements will be less attractive for a stiff potential as compared to a soft one.

The differences in the predictions for the binding energies are enhanced, if we compare the saturation points, i.e. the minima of the energy versus density curves (left part of Fig. 1), instead of the energies calculated at the empirical saturation density. Notice that the saturation points (solid symbols) determined from these modern potentials fall on the so-called Coester band [12].

The main interest of the present study is to explore the effects of ISB in these modern NN interactions. For that purpose we repeated the BHF calculations of nuclear matter replacing the pp and nn interactions by the corresponding matrix elements of the pn interaction, i.e.,

we assume perfect isospin symmetry and identify the NN interaction with the pn interaction. If we denote the energy from this isospin symmetric calculation by E_{BHF}^{np} , then we may define an energy correction which is due to the breaking of isospin-symmetry by

$$\Delta E_{ISB} = E_{BHF} - E_{BHF}^{np}. \quad (1)$$

Results for this energy correction are displayed in Table I and the right part of Fig. 1.

The energy correction is repulsive reflecting the fact that the pn interaction is more attractive in the partial waves with isospin $T = 1$ than the corresponding pp and nn interactions. A main contribution of this ISB can be related to the pion-exchange contribution, which is repulsive in the dominant 1S_0 partial wave. While the one-pion-exchange (OPE) contribution to the pp and nn interaction can only be mediated by the neutral pion π^0 , charged pions π^\pm can be exchanged in the pn interaction. Since the mass of the π^0 is smaller than the mass of π^\pm , the OPE contribution is more repulsive in pp and nn than in the pn interaction [13]. The ISB effect is largest and essentially identical for the CDBonn and Nijm1 potentials (the two curves referring to these potentials can hardly be separated in the right part of Fig. 1). It is weaker by roughly 35 percent for the potentials Nijm2 and Reid93, while the prediction of the Argonne V18 potential is in between.

Since the Argonne V18 potential is local, one would expect that it predicts ΔE_{ISB} very similar to the other local potentials, Nijm2 and Reid93. However, while the latter two potentials both predict $\Delta E_{ISB} = 0.22$ MeV, the ArgV18 result is 0.28 MeV, at $k_F = 1.36$ fm $^{-1}$ (cf. Table I). The reason for this discrepancy is as follows. Since the pp data are the most precise and reliable ones, all new high-precision ISB potentials are produced by first constructing the pp version of the NN potential with an accurate fit to the pp data. The $T = 1$ np potential is then *defined* as the pp potential, but with the π^0 exchange replaced by the π^0/π^\pm exchanges appropriate for $T = 1$ np and with one proton mass replaced by a neutron mass. The change in OPE explains about 50% of the empirically known difference between the pp scattering length (corrected for electromagnetic effects) and the np one, in the 1S_0 state. The remaining 50% can—to a large extent, but not completely—be explained

from ISB that emerges from 2π and $\pi\alpha$ exchanges where α denotes a heavy meson [1,13]. However, in the current high-precision NN potentials the latter is not included as derived from a microscopic model [13]; instead, what is missing to get the 1S_0 np scattering length right, is just fitted by enhancing a parameter in the model that describes the intermediate range attraction. Since the Nijmegen and the CDBonn potentials are constructed in a partial wave basis, this fitting affects only the 1S_0 state, making this state more attractive for np . The procedure is different for ArgV18. The Argonne V18 potential is constructed in a (S, T) decomposition (where S denotes the total spin and T the total isospin of the two-nucleon system). For getting the 1S_0 np scattering length correct, the $(S = 0, T = 1)$ potential is made slightly more attractive. However, in terms of a partial wave decomposition, this implies that all partial wave states with $(S = 0, T = 1)$, namely, 1S_0 , 1D_2 , 1G_4 , etc., have their attraction enhanced. This increases the binding energy obtained from the Argonne np potential (as compared to np potentials that adjust only 1S_0) and, thus, leads to a larger ΔE_{ISB} of 0.06 MeV for ArgV18.

The discussion of the previous paragraph raises the question, what change in ΔE_{ISB} is obtained if the ‘correct’ ISB in partial waves other than 1S_0 is applied (instead of just extrapolating what fits the np singlet scattering length). Unfortunately, we do not have any reliable empirical information on the ISB of the nuclear force in partial waves with $L > 0$ (where L denotes the total orbital angular momentum of the two-nucleon system), at this time. However, there are microscopic models that predict ISB. If those models predict the empirically known ISB of the 1S_0 scattering about correctly, then one may imply that the predictions for higher partial waves are also reasonable. One such calculation is published in Ref. [13], which is based upon the Bonn full model for the NN interaction [14]. A refined version of the CDBonn potential [15] has been constructed (that has become known as the “CDBonn99” potential [16]) which takes the ISB effects as predicted in Ref. [13] in partial waves with $L > 0$ into account and, in addition, includes the ISB effects from irreducible $\pi\gamma$ exchange as derived in Ref. [17]. We have used this CDBonn99 model [15] (in short: ‘CDBo99’) in our calculations as well and obtain $\Delta E_{ISB} = 0.370$ MeV at $k_F = 1.36$ fm $^{-1}$

(see table I). This is to be compared to 0.329 MeV as obtained from the ordinary CDBonn [5]. Thus, the refined treatment of ISB in partial waves higher than 1S_0 increases ΔE_{ISB} by 0.04 MeV.

A comparison with the Argonne V18 result discussed above implies that ArgV18 contains a reasonable estimate for the ISB effects from higher partial waves. ArgV18 is overestimating the ISB effect from higher partial waves by roughly 50%. The reason for this is presumably that the ISB term in the ArgV18 potential (that describes ISB beyond OPE in a phenomenological way) is too long-ranged.

The effect of ISB is also reflected in the saturation points displayed in the left part of Fig. 1. While the filled symbols refer to the saturation points predicted from the calculation with inclusion of the ISB terms, the open symbols are obtained for the corresponding E^{np} . The effect of the ISB terms on the calculated symmetry energy (difference between binding energy per nucleon of neutron matter and nuclear matter at the same density) is negligible (see Table I).

The NN interactions CDBonn and ArgV18 have been adjusted to reproduce the differences in the scattering length and effective range parameters for pp and nn scattering. Therefore these two potentials as well as the NN interaction CDBonn99 also yield significant differences in predicting the single-particle potentials for protons $U_p(k)$ and neutrons $U_n(k)$ as a function of the momentum k in symmetric nuclear matter. It turns out that the momentum dependence of the difference

$$\Delta U_{CSB}(k) = U_p(k) - U_n(k), \quad (2)$$

is weak. Therefore we display in Fig. 2 this difference just calculated at the Fermi momentum $k = k_F$ for various densities. This difference is positive, which implies that the pp interaction is less attractive than the corresponding nn interaction as one can already deduce from the difference in the 1S_0 scattering lengths ($a_{pp} = -17.3$ fm compared to $a_{nn} = -18.8$ fm) [18].

At the empirical saturation density, the ArgV18 and CDBonn99 predict a value for ΔU_{CSB} of 0.31 MeV and 0.28 MeV, respectively, while the CDBonn potential yields 0.16

MeV. These numbers should be compared with a value of 0.2–0.3 MeV, which is typical for the Nolen Schiffer anomaly, i.e. the energy difference between the binding energies of mirror nuclei, which is beyond the effects of the electromagnetic interaction [2]. It seems that the BHF predictions based on the three potentials yield the right order of magnitude.

At a first glance, it is disturbing that some predictions differ by almost a factor of two. However, this can be explained. The reason is similar to what we discussed above in conjunction with ΔE_{ISB} . In all models, the construction of the nn potential starts from the pp potential. To fit the slightly more attractive 1S_0 nn scattering length, the attraction in the potential is slightly enhanced. In the case of the Argonne V18 potential, this implies more attraction for all ($S = 0, T = 1$) nn partial waves. The CDBonn99 potential, which contains the microscopically determined CSB effects, predicts different interactions in all $T = 1$ partial waves. In the CDBonn, strictly only the 1S_0 state is made slightly more attractive to match a_{nn} . This explains the larger value for ΔU_{CSB} obtained for ArgV18 and CDBonn99. Obviously, CSB in partial waves higher than 1S_0 is of considerable influence on ΔU_{CSB} .

Therefore our conclusion is the following: to reproduce the Nolen Schiffer anomaly, it is insufficient to take just the CSB in the 1S_0 scattering length into account; a distinguished knowledge of CSB in partial waves beyond 1S_0 is crucial.

In summary, we have calculated ISB effects in nuclear matter and find that they are generally small, but important in some cases. For the binding energy per nucleon in symmetric nuclear matter, the breaking of isospin-symmetry is a very small effect. For all the potentials analyzed in the paper, ISB produces a small loss of binding energy (as compared to calculations that use the np potential throughout), which is mainly caused by the ISB in the 1S_0 partial wave. The effects in the symmetry energy are essentially negligible. On the other hand, if one wants to explain the Nolen Schiffer anomaly by calculating the difference between the single particle potential for protons and neutrons, which is a measure for charge symmetry breaking, one finds that, in order to have quantitative agreement, it is necessary to include CSB in partial waves beyond 1S_0 . A natural way to incorporate CSB in higher

partial waves, based on microscopic calculations, is provided by the recent update of the CDBonn potential that has become known as the CDBonn99.

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TABLES

	E_{BHF}	E_{HF}	ΔE_{ISB}	E_{Sym}	E_{Sym}^{np}
CDBonn	-16.78	6.06	0.329	30.65	30.45
CDBo99	-16.83	6.09	0.370	30.56	30.36
ArgV18	-15.58	31.73	0.282	29.74	29.77
Nijm1	-15.48	13.04	0.329	29.43	29.16
Nijm2	-13.71	35.62	0.221	28.08	27.84
Reid93	-14.28	35.46	0.218	28.24	28.21

TABLE I. Energies calculated for nuclear matter with Fermi momentum $k_F = 1.36 \text{ fm}^{-1}$. Results are listed for the energy per nucleon calculated in BHF (E_{BHF}) and Hartree-Fock (E_{HF}) approximation, the loss of energy per nucleon due to the breaking of isospin-symmetry [ΔE_{ISB} as defined in Eq. (1)], the symmetry energy with (E_{Sym}) and without (E_{Sym}^{np}) inclusion of ISB. All entries are in MeV.

FIGURES

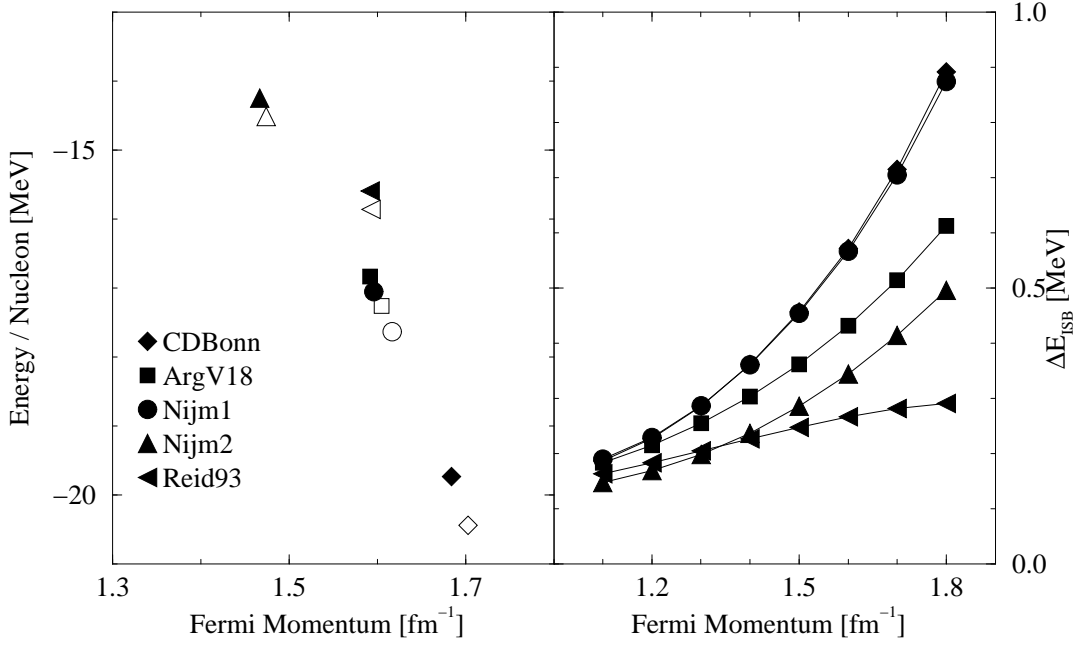


FIG. 1. The left part of this figure displays the saturation points for symmetric nuclear matter evaluated in the BHF approximation for various NN interactions. Filled symbols represent the results for the interaction with inclusion of ISB, while open symbols are obtained if the pn interaction is used for all two-nucleon pairs. The right part of the figure shows ΔE_{ISB} as defined in Eq. (1).

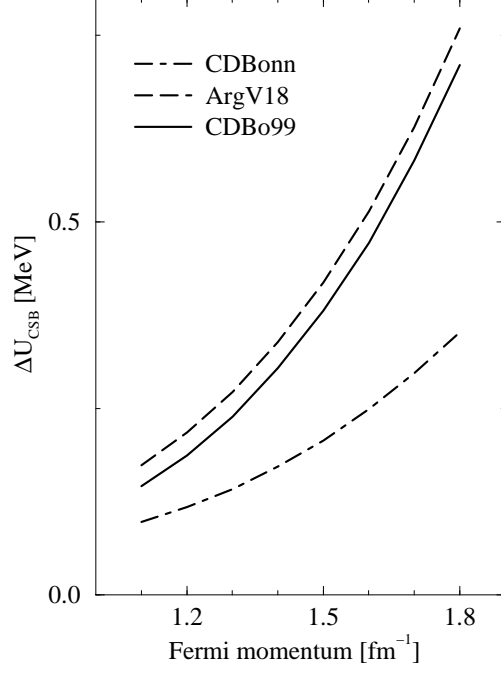


FIG. 2. Difference between the single-particle potentials for protons and neutrons ΔU_{CSB} [as defined in Eq. (2)] calculated at $k = k_F$ for various densities and three different NN potentials.